AN AIRCREW HYPOXIA-WARNING SYSTEM

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INTRODUCTION

The hazard to flying personnel resulting from exposure to low oxygen pressure is widely recognized, and aircraft accidents attributable to hypoxia remain prevalent when compared with other biomedical causes (1, 2, 3). Considering, however, its insidious nature and its fulminating character at high altitudes (see figure 1), the conspicuous incident of hypoxia in military flying is not surprising.

In principle, the use of pressurized aircraft with auxiliary oxygen equipment should offer completely satisfactory protection against the occurrence of hypoxic episodes. In practice, however, a number of factors, including malfunctioning equipment, improper mask fit, and lack of adequate indoctrination can modify the situation and enhance the risk of hypoxia during flights at high altitudes. Because of this, considerable attention has been focused on finding an acceptable air-borne instrument which could warn of impending hypoxia in time for corrective action to be taken. Obviously, no amount of instrumentation can substitute for proper engineering and maintenance of oxygen equipment, or for proper indoctrination in its use. Such instrumentation can, however, serve as a basis for objective evaluation of each of these functions as well as a monitor of overall operation of the oxygen equipment system during potentially hazardous flight operations.

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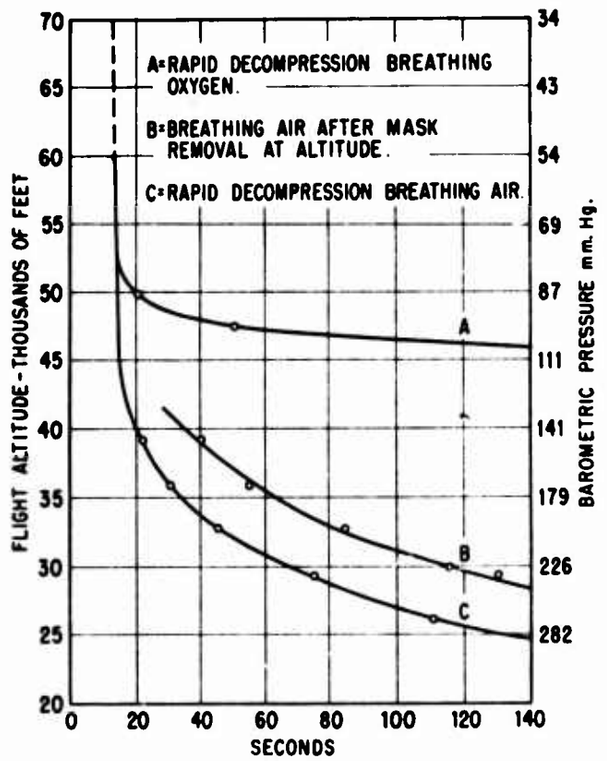


FIGURE 1

Time of useful consciousness.

This paper will describe an aircrew hypoxia-warning system based on the use of an electrochemical oxygen sensor within the oxygen mask. The signal from this sensor, after amplification, controls a relay which is set to activate a warning panel light at a predetermined level of oxygen partial pressure. In contrast to a photoelectric system previously tested (7), preliminary evaluation of the electrochemical device during actual flight conditions indicates that reliable information is obtained without the need of continual adjustment or calibration of the equipment. Such results support the belief that the unit may be suitable for general use as an aircrew hypoxia-warning system.

DESCRIPTION

Figure 2 shows the complete unit with the oxygen sensor installed in a regulation oxygen mask. Neville (4) has described the sensor,

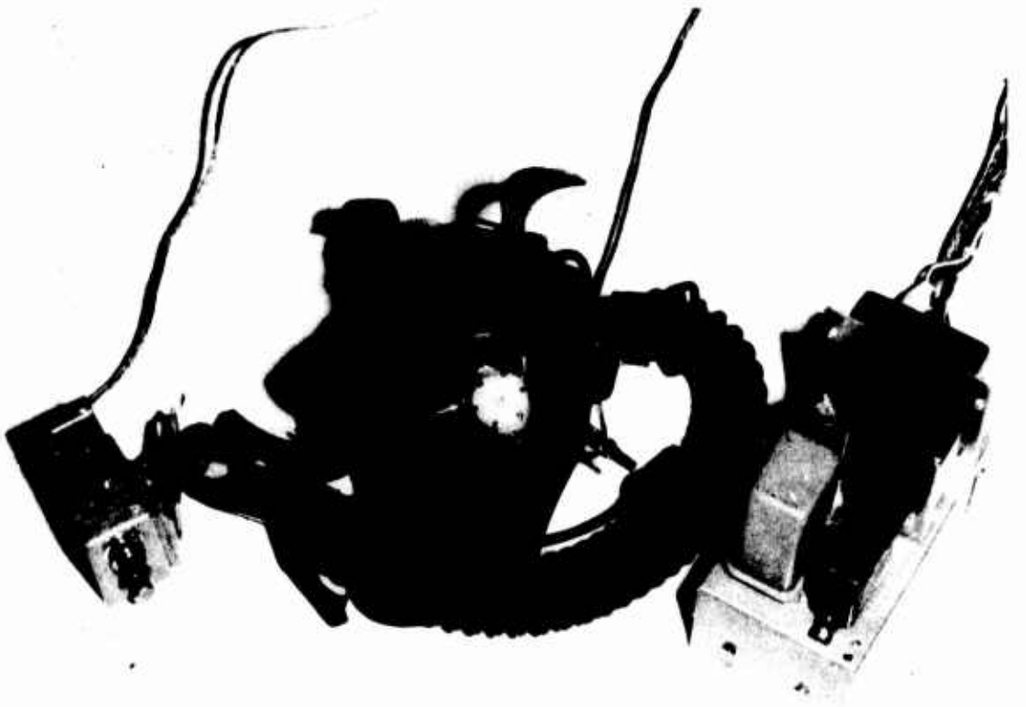


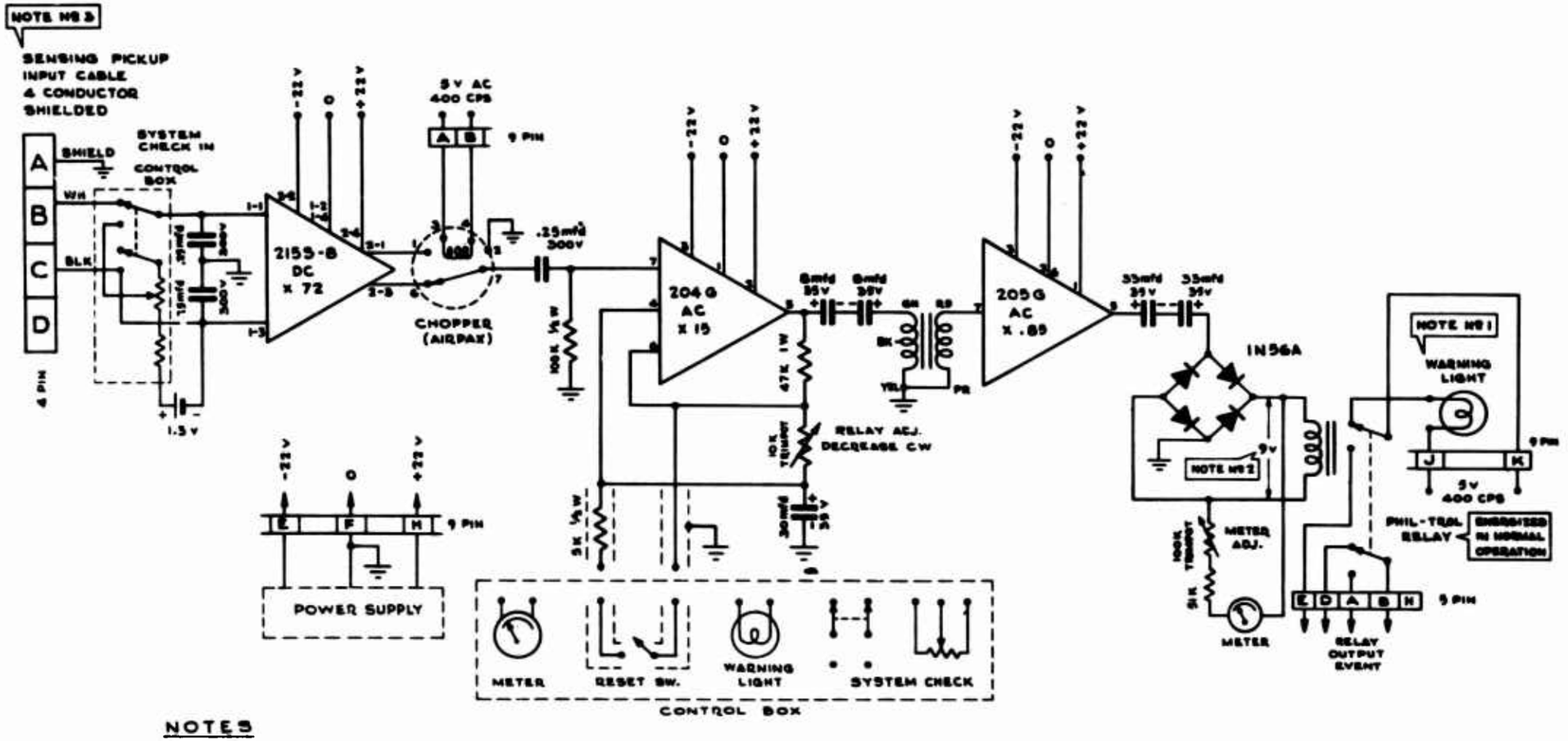
FIGURE 2

Hypoxia-warning equipment showing sensor in mask.

and the reader is referred to this source for details. It is worth noting that the size of the sensor can be made small enough to fit comfortably within the oxygen mask and that there is no interference with other mask functions. In the tests described in a later section, the insulated electrical cable is simply taken out through a small hole punched in the chin region of the mask beside the exhalation port. An effective seal is formed and no leakage occurs even with pressure-breathing conditions. Not shown in figure 2 is a cable connector assembly which permits convenient separation of the mask-sensor unit from the electronic equipment. The equipment shown in figure 2 and schematically presented in figure 3 was that used in the evaluation described. A number of improvements have been incorporated in recent designs, however, and these have resulted in more compact units requiring less power. Since such improvements will no doubt continue, it seems worthwhile for our purpose to indicate only the general requirements of the system rather than to go into the details of a specific unit.

The effect of temperature on the oxygen cell has been compensated by inserting a thermistor in the external circuit of this unit. The value of this thermistor will be about 5 K. ohms at 25° C. Compensation is obtained through the directly opposite effect that temperature displays upon the value of the current generated by the cell and upon the resistance value of this thermistor. The voltage drop tends to remain constant at constant Po_2 regardless of temperature change. Since voltage is measured rather than current, the first requirement of the electronic system will be a high input resistance. Optimally, this input resistance should be at least 0.5 megohm or more, but 100 K. ohms will normally satisfy most requirements.

As the sensor is an electrochemical device, the current generated by the sensor will be affected by the voltage applied to its electrodes. Since polarographic principles are used, however, there exists a so-called plateau region where the current is limited by diffusion of oxygen. A voltage change in this region will



NOTES

1. WARNING LIGHT IN BOX WITH RESET BUTTON.
2. RELAY OPENS WHEN OUTPUT VOLTAGE DROPS, TURNING ON WARNING LIGHT.
3. CONNECT SENSOR BEFORE TURNING ON EQUIP. TO PREVENT SURGE VOLTAGE.

FIGURE 3

Wiring diagram for hypoxia-warning device.

not affect the current. This plateau region is only about 0.5 volt wide. It is obvious, therefore, that care should be exercised in the design of the initial stage of the amplification system in order to give full consideration to this important parameter affecting the operation of the sensor.

The use of the system in high performance aircraft will, of course, require that the equipment be unaffected by vibration, shock, or acceleration. The amplifier gain should be a substantially constant factor over a broad temperature span. Since the basic signal of the transducer is a direct current, the amplifier design must allow for zero shifts which commonly afflict d.c. amplification systems. Mechanical choppers are probably the most effective means of overcoming this difficulty. The unit shown here incorporates mechanical chopper stabilization.

The actual warning mechanism used in the present device is a red light. This light is controlled by a relay; the relay, in turn, is energized by the output signal from a power amplifier. One problem associated with use of the relay is the difference between the pull-in and drop-out current. The relay can be set to close the warning-light circuit at a given P_{O_2}; however, once the relay drop-out current has been reached, the pull-in current required to re-establish a nonwarning condition may be 1½ or 2 times the drop-out current. Under some operational conditions, this would be impossible to attain even if effective corrective action had been carried out after a warning was rendered. Therefore, as in the device used in the evaluation described in this paper, an automatic reset button is used to circumvent this shortcoming of the relay. This will momentarily decrease the feedback resistance which increases the gain of the amplifier enough to reset the relay. Another solution, used more recently, is to install a relay in which the ratio of pull-in to drop-out current is much closer to 1, thus obviating the need of a manual reset. Such "micro-positioner" relays have been subjected to vibration tests and appear suitable for use in air-borne operations.

EVALUATION PROCEDURE

Functional assessment of the hypoxia-warning unit described in the previous section naturally involves a number of related stages of testing. True effectiveness of the unit must finally be judged by performance during actual flight operations of sufficient number to decide to what extent its use can improve flying safety. For full effectiveness, a number of auxiliary problems such as installation, calibration, maintenance, storage, and replacement must be studied in order that any special requirements can be tailored to the needs of the system. Such types of evaluation are beyond the scope of the present work. This report deals with preliminary observations and discusses possible problem areas related directly to the functional capacity of the unit itself.

The performance characteristics of the oxygen sensor used in the hypoxia-warning unit have been discussed elsewhere (4). Bench tests and altitude-chamber studies have indicated that the sensor or transducer can perform adequately when used as the detector in the aircrew hypoxia-warning system described here. Effects of vibration, G-forces, shock, pressure, and temperature changes have been investigated and are discussed in the report cited above.

The temperature effect is perhaps the most critical factor involved in the use of the transducer in an hypoxia-warning system. Although the unit has performed successfully within a temperature range of approximately 30° to 140° F., little information is available on its operation outside these limits. Higher upper limits are tolerated, but the effects of such temperatures on the functional characteristics have not been examined at any length. Low temperature limitations are related to freezing of the electrolyte, a change in state that alters the function of the cell drastically. Normal operation will return when the electrolyte thaws, but the effects of repeated freezing and thawing cycles have not been studied.

Actually, since the unit is placed within the mask where gas at or near body temperature is continually flowing across it, the operating

temperature can be expected to be within tolerable limits under most circumstances. The greater temperature extremes would normally be expected to occur when the device is not in use. For example, when the unit is left in the cockpit of an aircraft on the flight line at Thule, Greenland, or at Edwards AFB, Calif., the unit would be exposed to considerable extremes of temperature.

Although a number of possible means are available for increasing extreme temperature tolerance, there are practical limits to which such effort could be carried. As now constituted, the temperature span in which the device will perform satisfactorily covers a considerable portion of the span set by such limits. Therefore, a more realistic approach to this problem would seemingly involve indoctrination of crew members in procedures designed to protect the device and extend its operational life. Such procedures could be relatively simple and designed to be a part of the usual indoctrination program related to personal equipment. To be effective, such indoctrination must depend on demonstrating the contribution which the hypoxia-warning device can make to flying safety. It is to this latter problem that we now turn.

Two flights in an F-100 type research aircraft were performed to gather preliminary in-flight data and to determine whether any gross malfunction would occur. The pilot of the aircraft flew a prescribed course, and a rear cockpit passenger used the hypoxia-warning device and performed the maneuvers described below. The subject using the hypoxia device was a flight surgeon capable of recognizing signs of hypoxia at an early stage. Each flight lasted approximately one and one-half hours, the highest flight altitude attained being 47,000 feet. Cabin altitude did not exceed 30,000 feet. The two flights differed slightly with regard to the maneuvers performed and the manner of performance; however, except for a preset change in the level of warning by the hypoxia device, the two flights were essentially the same. In the first flight, the unit was preset to warn when the oxygen partial pressure sensed by the transducer fell to approximately 70 mm. Hg. In the second flight this level was preset to 90 mm. Hg P_{O_2}. With regard to such settings, it is important to realize that the response time of the device is generally fast enough to indicate the changes in mask partial pressure that occur during the breathing cycle. This being so, it is readily apparent that the particular setting chosen must be referred to the expired portion of this cycle, or, more exactly, to the partial pressure of oxygen in the end-expired gas. Since this latter will reflect the state of oxygenation of the blood more accurately than any other portion of the cycle, the necessity of referring the warning level to expired gas engenders little difficulty. This point, together with related factors, will be discussed in more detail later.

The first flight was performed with the cabin pressure differential maintained at 2.75 p.s.i. In the second flight, the 2.75 p.s.i. differential was used only to 11,000 feet, the flight to higher altitudes up to 30,000 feet being performed without pressurization.

Three basic maneuvers were performed to produce an irregularity in the operation of the oxygen system: mask removal, mask leak, and maskhose disconnect. In the case of mask removal, the subject turned it away from his face after removal. In some cases the air in front of the mask was fanned with the subject's hand to effect a more rapid gas mixing; in other cases this fanning was not performed. The mask leak was generated by inserting a finger between the lower jaw and the mask. Each maneuver was timed, the cabin altitude was observed, and note was made of whether or not a warning was elicited. Except for one instance, no maneuver lasted more than one minute. Whenever a warning was obtained, the maneuver was terminated. Table I lists the results obtained with the unit during the two flights. No malfunction of any kind was detected during the flights.

RESULTS AND DISCUSSION

Table I shows several points worthy of comment. First, with mask removal, the warning altitudes of 22,000 feet (first flight)

TABLE I

Flight No. 1

Sensor set to warn at 70 mm. Hg P_{O_2}

Cabin altitude (ft. × 10^3)	Maneuver	Time maneuver performed (sec.)	Warning	Ambient P_{O_2} (mm. Hg)
2	*Mask off	30	–	148
4	*Mask off	50	–	137
6	*Mask off	45	–	128
8	*Mask off	44	–	118
10	*Mask off	45	–	110
12	*Mask off	55	–	101
14	*Mask off	50	–	93
16	*Mask off	56	–	86
20	*Mask off	40	–	73
22	*Mask off	12	+	67
24	*Mask off	7	+	62
26	*Mask off	4	+	56
27	Mask leak	22	+	54
28	Mask leak	32	+	52
28	*Mask off	2	+	52

Flight No. 2

Sensor set to warn at 90 mm. Hg P_{O_2}

3	Mask off	30	–	142
6	Mask off	45	–	128
9	Mask off	45	–	113
12	Mask off	45	–	101
15	Mask off	37	+	88
20	Mask off	8	+	73
20	Mask leak	28	+	73
25	Mask off	3	+	59
25	Mask leak	31	+	59
30	Mask off	120	–(1)	47
30	Maskhose disconnect	9	+	47
25	Mask off	7	+	59
20	Mask off	7	+	73
15	Mask off	22	+	88
15	Mask off	17	+	88
15	*Mask off	8	+	88
15	*Mask off	9	+	88
15	*Mask off	6	+	88

* Sensor and mask fanned.
(1) Regulator delivering positive oxygen pressure.
– No warning.
\+ Red light on.

and 15,000 feet (second flight) are highly consistent with the 70 and 90 mm. Hg warning settings established for the respective flights. No false positive effects were obtained during either flight and the difference between the 20,000-foot (no warning) and 22,000-foot (warning) altitudes during the first flight is only about 6 mm. Hg oxygen. On the basis of the limited data presented, it is not possible to determine the reproducibility of the warning level with any confidence. Since, in both cases, the ground-level setting was verified to the precision indicated above, further in-flight evaluation is encouraged. Readings were actually taken on the way down as well as on the way up, but were noted in table I only when

there was a significant difference in time of warning (such differences can be partially explained as discussed below). Controlled laboratory experiments indicate that the reproducibility of the transducer can be as small as 1 or 2 mm. Hg oxygen (4). Even if it were possible to attain such figures during in-flight use, however, such limits would be unrealistic in terms of the application as a hypoxia-warning device. Limits of ± 10 mm. Hg at the 95 percent confidence level would probably be highly satisfactory for such application.

The time column of table I shows that in all appropriate cases the warning was obtained well in advance of the limit set by the time of useful consciousness curve (fig. 1). The one seeming exception is the result at 30,000 feet during the second flight with the mask off. Here the D-2 oxygen regulator was delivering oxygen under safety pressure so that mask removal simply resulted in a continual outflow of this gas, and the oxygen partial pressure within the mask did not fall to the warning level. Note the remarkably different result at the same altitude but with maskhose disconnect.

The time taken to cause a warning was not always identical for what were apparently equivalent cases. This difference is attributable, at least in part, to the method of mixing or equilibration of the different gas spaces involved. For instance, the so-called "washout" time of the lungs may influence the time of warning as could the exact point during the respiratory cycle at which a given maneuver was started. The gross time differences obtained during mask removal, with and without fanning, emphasize the importance of mixing and equilibration. For practical purposes, any delay in warning is governed by the above factors and not by the response constant of the unit, the latter being of the order of two seconds or less (4).

In view of the relationship between the warning setting and the respiratory cycle, the "mask-off" maneuver is not a truly functional test of the equipment. While it is unlikely that this maneuver would normally occur (except in a situation where a hypoxia warning would be superfluous), it served as a rough check on the warning-level setting and response time. Under normal conditions of mask use, the warning settings of 70 and 90 mm. Hg oxygen tension would be equivalent to a warning while breathing ambient air at about 8,000 and 2,000 feet, respectively, because the sensor would be exposed to end-expired air when the mask is on. The fact that a warning can be given at such relatively low altitudes in the absence of false positives insures that the longest possible time will be available for effective countermeasures in the event of malfunction of the oxygen system.

Since it is generally desirable to keep the oxygen partial pressures in lungs of aircrew members at or near sea level equivalents, it is felt that the 70 to 90 mm. Hg level is a reasonable range in which the warning should be set. Higher settings might well lead to a high percentage of false positive warnings (in a sense that no true malfunction existed). Lower settings, on the other hand, could miss borderline hypoxia when fatigue and decline in judgment may play an important role in crew performance. A further danger of having a setting too low would result should a crew member be lulled into a false sense of security upon discovering that hyperventilation could prevent a warning. Whether hyperventilation was voluntary or involuntary would make little practical difference, and the resulting hypocapnia might be seriously detrimental to performance without a warning being elicited. Normal hyperventilation resulting from alveolar-oxygen pressures in the 70 to 90 mm. Hg range is probably not significant (5). It is true, of course, that hyperventilation may be triggered by factors other than low-oxygen pressure. Such cases are independent of the oxygen pressure requirements, however, and should not influence the warning-level setting based on such requirements.

If large numbers of individuals make use of the hypoxia-warning device, then supposedly the absolute optimum setting for each would constitute an array of values about some norm. Thus, in theory, the extent and shape of any such distribution would need to be taken into

account when deciding on a standard warning setting. In practice, however, it is unlikely that such precise statistical evaluation would be necessary. In the first place, the most likely candidates for use of such equipment are highly selected individuals having a minimum of respiratory pathology. The high homogeneity of the group indicates that deviations from the norm would not be significant. More importantly, the oxygen concentration, which can be considered borderline from the standpoint of hypoxia, is reasonably well recognized. Between such an oxygen concentration and that which would be equivalent to ground level, there is a relatively large safety range because of the peculiar shape of the oxyhemoglobin dissociation curve. This range amounts to perhaps 30 mm. Hg alveolar-oxygen pressure (i.e., 70 to 100 mm. Hg). To avoid false warnings, a buffer zone of at least 10 mm. Hg would be desirable between the normal level of 100 mm. Hg alveolar P_{O_2}, which the oxygen equipment attempts to maintain, and the warning level. Since, prima facie, one would assume that a warning level as high as possible consistent with a minimum number of false warnings would be desirable, then a setting of 90 mm. Hg oxygen pressure seems indicated. There are a number of instances, however, when it might be desirable to have a lower setting, particularly under combat conditions where functional performance of the crew may have to be pushed to the limit. Also, it is more practical to plan in terms of a device which has a setting reproducibility of $\pm$ 10 mm. Hg oxygen pressure, in which case an 80 mm. Hg warning level should warn at the indicated hypoxia borderline of 70 mm. Hg, or above, and should also prevent the occurrence of a significant number of false positives.

Another problem regarding application of the hypoxia system relates to presenting the signal to the crew member once a warning has been effected by the unit. The simplest method would probably be a red light placed at some appropriate site. Vision, however, is usually the first sensory element to deteriorate with hypoxia. The auditory function, on the other hand, is relatively resistant to low oxygen (6), and an auditory cue is, therefore, preferable. A combination of both an auditory and a visual signal probably would be the least equivocal. The use of any other sensory pathway, however, appears to present too many problems to be practical. While automatic control or response may be feasible for certain sealed environment applications, this approach does not appear feasible with the oxygen systems presently used in operational aircraft.

Since different approaches have been made to the problem of aircrew hypoxia warning, it is appropriate to comment on these and make comparisons with the present system when possible. Actually, most of the systems that have been proposed in the past have depended upon observations made directly upon the physiologic state of the subject (i.e., blood-oxygen saturation, electroencephalogram, etc.). The inherent disadvantages of this method are twofold. First, the sensor or transducer must be attached directly to the subject. Not only is this distracting, but it can also be physically discomforting. Secondly, it is generally true that no warning can be given until at least some deterioration in the physiologic state has already occurred. This may be too late for effective countermeasures. For instance, in an evaluation of an ear-oximeter type of hypoxia-warning device, Bancroft et al. (7) found warning times which varied between 34 and 542 seconds under simulated oxygen-mask malfunctions in an altitude chamber. The warning level in these experiments was set between 80 and 90 percent arterial-oxygen saturation. The percent saturations actually observed at warning ranged from 79 to 94 percent. We have seen previously that the electrochemical hypoxia-warning device can be set to warn in a range at least as small as 6 mm. Hg oxygen pressure at a level equivalent to 90 mm. Hg in the alveolar gas. Assuming this is representative of the arterial-oxygen pressure, a normal oxygen dissociation curve indicates that this would be equivalent to an arterial blood–oxygen saturation level of 96 percent. A decrease from this level of 20 mm. Hg, easily detectable with the electrochemical hypoxia-warning device, would result in only a 3 or 4 percent decrease in the blood-oxygen

saturation level. Such a change would be extremely difficult to measure accurately with the ear oximeter under conditions imposed by high performance aircraft.

Further comparison of the evaluation data of Bancroft et al. with that in this paper also suggests the advantage of the electrochemical device from the standpoint of delay or warning time. This advantage is compounded by the fact that the mask detector measures further "upstream" from the critical physiologic events than is possible with a device which must depend on a change of these same physiologic events for its operation.

Whatever the apparent advantages of the electrochemical device, it must be admitted that the data in table I are not numerous enough to be taken as conclusive, and further tests are needed. While repeated laboratory studies indicate that both the transducer and the associated electronic gear will perform adequately for extended periods under conditions similar to those imposed by high performance aircraft, adequate confirmation of this under actual flight conditions is desirable before any widespread application of such equipment is attempted.

SUMMARY

An aircrew hypoxia-warning system has been described in detail. In-flight data obtained with this system during evaluation procedures carried out in an F-100 type research aircraft are presented. The warning system and the evaluation data are discussed in terms of some of the important operational features and requirements. The device is shown to give satisfactory warning of any situation tending to lower mask oxygen pressure below a given preset critical level.

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